CHAPTER II

OPTICAL DETECTION OF MOVING STRIATIONS WITH THE CROSS-CORRELATION TECHNIQUE

by

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SUMMARY

Optical observations of emission variations in a plasma generated by a glow discharge have been achieved using the cross-beam correlation technique. Classification of these emission variations at a point into periodic, narrow band, and random processes, is discussed, along with the identification of convection speeds and feedback loops of the system.

II-1. INTRODUCTION

The experiments documented in this paper were designed to develop cross-beam methods for studying local photo-chemical processes in a plasma. Previous investigations of glow discharges by Abria [II-1] and later by others [II-2] indicated that it is composed of moving optical fluctuations. More recent photographic experiments by Garscadden and Lee [II-3] show that these fluctuations can move both toward the cathode and toward the anode. Our tests differ from previous investigations by applying the cross-beam correlation technique which was developed in the wind tunnel by Fisher and Krause [II-4] and in the atmosphere by Stephens *et al.* [II-5] to measure wind speeds. Velocity and frequency information has been obtained by extending the cross-beam technique from extinction processes to emission processes.

II-2. PHOTOGRAPHIC EVALUATION OF GLOW DISCHARGE PHENOMENA

The plasma instabilities that produced the optical fluctuations are defined to be striations in the positive column of the glow discharge (see Fig. II.1). Stationary striations, which are packets of ionized gas separated by dark spots, normally occur at tube pressures below 1 mm Hg (see Fig. II.1b). Figure II.1a is an example of moving striations. Although this picture was taken at 1/100 of a second, fluctuations are not obvious, and the glow appears as a continuum. Figure II.2 shows the test setup as it appeared immediately before a high-speed movie was taken.

If a striation contains an excess of positively ionized gas, it should move toward the cathode. Conversely, if a striation contains an excess of electrons, it should move toward the anode. This is in accord with the current views of plasma physics [II-3]. These two cases are illustrated in Figures II.3 and II.4 taken at 1/400 of a second. In Figure II.3 the smaller striation moves primarily toward the cathode, reverses its direction for a short time, and moves backward toward the anode. In Figure II.4 the movement of the striation tends entirely toward the anode. This is in keeping with the results of Garscadden and Lee [II-3] which show existence for forward- and backward-moving striations.

High-speed movies were taken of this phenomenon, but, unfortunately, movies provide only qualitative descriptions since the photographic film is a logarithmic detector. Therefore, one cannot see a fine structure in the photographs of the large semi-stationary ionization. The present state-of-the-art in photography restricts measurements to those occurring below 1000 Hz. For example, little or no detailed information can be obtained about a glow discharge in argon since its frequency range is from 1000 Hz to at least 10,000 Hz.

II-3. CROSS-BEAM EXPERIMENTS

Both qualitative and quantitative results have been achieved by using two crossed photomultipliers. These photomultipliers are linear over their entire range and have a frequency response better than our electronics.

The experimental setup is shown in Figure II.5. Our measurements, which were restricted to the positive column, were made at an optical wave length of 3100 Å with a bandpass of 50 Å. The focal length of the optics was 11.3 cm with a diameter of the beam at intersection of 1 mm. The work was done in a discharge tube of a diameter of 9 cm and with

stainless steel electrodes 82 cm apart. The major portion of our effort was concentrated in Argon at the pressure range from 1 mm Hg to 25 mm Hg, with some work also being done in CO_2 and air.

The outputs of the optical collectors were then fed into the Princeton Applied Research (PAR) analog correlator to obtain a covariance reading. This on-line analog computer assumes that no D.C. shifts, trends or gain instabilities were introduced by the electronics. Further, the covariance thus obtained will become uncertain as soon as the correlation drops below 10 percent of the mean signal power.

Within the above assumptions, the analog computations of the PAR correlator should form an estimate of the temporal covariance function, which is defined as follows:

$$\overline{\overline{C_{xy}}}\ (\tau) = \frac{1}{TN}\int_{o}^{T} (X(t) - \bar{X})(Y(t-\tau) - \bar{Y})\ dt,$$

where

$x(t)$ = instantaneous fluctuations of intensity from the undelayed channel

$Y(t-\tau)$ = instantaneous fluctuations from the delayed channel

$\bar{X}$ and $\bar{Y}$ = average values of the fluctuations

τ = delay time set during data reduction

t = real time

T = total integration time

N = normalization factor.

This covariance enables one to obtain the best estimate for the amount of time required for the striation to traverse the transit distance of the two beams (see Fig. II.5). The covariance also provides a systematic approach to the classification of narrow- and broad-band processes while systematically treating an entire ensemble.

As shown in Figure II.6 several types of wave form were encountered. The first signal is easy to classify since it is obviously periodic, but the remaining signals require some kind of statistical description. Figure II.7 shows how the top three signals can be classified by use of

an autocorrelation curve. When the maximum amplitude of the peaks does not decay as a function of time delay, then the process is periodic. When the peak decay is a function of time delay the process is either narrow-band or broad-band, depending on the rate of correlation decay. The broad-band process occurs where there is only a fundamental peak and the remaining peaks are washed out. In the narrow band process the higher order peaks decrease in amplitude as the order increases. Physically, these three processes tell you that:

(1) If the signal is periodic, then the signal time history is recurring at exact intervals of time.

(2) If the signal is narrow-band, then the time history will repeat itself for a finite number of periods until it is damped out.

(3) If the signal is broad-band, then the signal time history will not repeat itself.

Thus, the kind of process provides a means of classification of the internal consistency of the structure.

The fourth signal on Figure II.6 affords a more challenging test for the correlation technique as shown in Figure II.8. It was found that by filtering the signal it could be subdivided into a high frequency and a low frequency component. The low frequency component was due to periodic fluctuations and moved in the direction of the cathode. The high frequency component was a narrow-band process and had a velocity in the direction of the anode. This could well be thought of as an ion striation (moving toward the cathode) with a substructure composed of electron waves (moving toward the anode). The direction of flow was determined by starting with intersecting beams and increasing the beam separation. As the separation increased, the transit time increased positively or negatively according to the flow direction.

Another kind of measurement performed was the identification of the feedback loop between the fluctuations of the discharge current and the optical fluctuations in emission. This was done by cross-correlating the optical fluctuations with the current fluctuations. When the beam separation increased, the transit time increased (bottom correlation curve in Figure II.8). Thus, it was possible to close the feedback loop and say that the fluctuations in the current were due to the flow of electrons in the discharge.

When one changes the potential across the discharge, the discharge is unstable until it reaches thermal equilibrium. All of our measurements were made after a short period of time had elapsed, and it was confirmed that all parameters were stable.

II-4. PERIODIC STRIATIONS

The frequencies of the periodic fluctuations ranged from 10 Hz to 50 KHz and the velocities from 0 to 30 km/sec. The results are based on over 200 measurements, which are summarized in Figures II.9, II.10, II.11 and Table II.1.

During the course of our measurements, it was noticed that a periodic waveform would appear out of what had been a random narrow-band process. This periodic waveform was stable for the conditions under which it was observed, but any slight change in conditions resulted in a reversion to the random narrow-band process. The periodic process was observed in Argon over a wide range (1 mm - 20 mm) of pressure, but only certain discharge voltages for each pressure. It was also noticed that the amplitude of the periodic waveform was much larger than that for the associated random narrow-band process.

The wave length of the periodic waveform seemed to fall approximately into two categories (see Fig. II.10):

(1) Wave length equal to length of tube;

(2) Wave length equal to one half of tube length.

The velocity and frequency of the periodic striations are practically independent from the tube pressure within the range between 1 and 20 mm Hg as illustrated in Figures II.9 and II.10. The kind of process, the kind of striation (ion or electron), and the gas composition all have a first order effect on the velocity, frequency, and wave length of moving striations. Even though we could not clearly establish a pattern, there appeared to be times during which only one type of striation was present. Ion and electron striations did not always occur simultaneously.

II-5. STANDING STRIATIONS

The second distinct class of striation that was observed in the glow discharge is a standing striation. We always found that the fluctuations in emission associated with standing striations were broad band. The first zero crossing of the auto-correlation function was taken as an estimate of the time period associated with the center frequency of the broad band process. This period was divided into the measured velocity to obtain a characteristic wave length.

Although the striations appear standing to the observer, the cross correlation tests indicated that they have small velocities about a factor of a hundred less than those associated with the periodic striations. The direction of these small velocities seemed to follow only the electron flux.

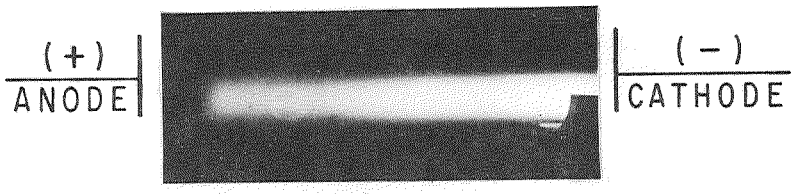
II-6. CONCLUSIONS AND RECOMMENDATIONS

Since our results for the velocities and frequencies of moving striations are in keeping with those to be found in the literature, we have confidence in the cross-beam technique to retrieve this information in emission.

This research has demonstrated the feasibility of the cross-beam technique for successful retrieval in emission of (1) phase and group velocities along the main current, (2) separation of periodic and random narrow-band components, (3) classification of optical disturbances using length and time scales in moving frame, (4) classification of flow instabilities through statistical evaluation of changes in surroundings, and (5) correlation between feedback loops and the control system (e.g., correlation of fluctuations in emission and fluctuations in current).

GLOW DISCHARGE

a.

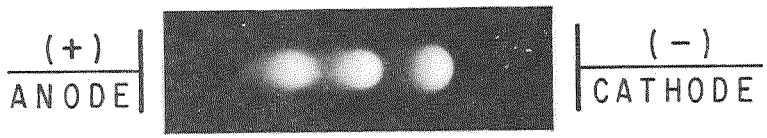


MOVING STRIATIONS IN ARGON

f = 24 KC v = 16 km/sec

p = 2 mm Hg

b.



STANDING STRIATIONS IN ARGON

p = 0.02 mm Hg

FIGURE II.1. MOVING AND STANDING STRIATIONS

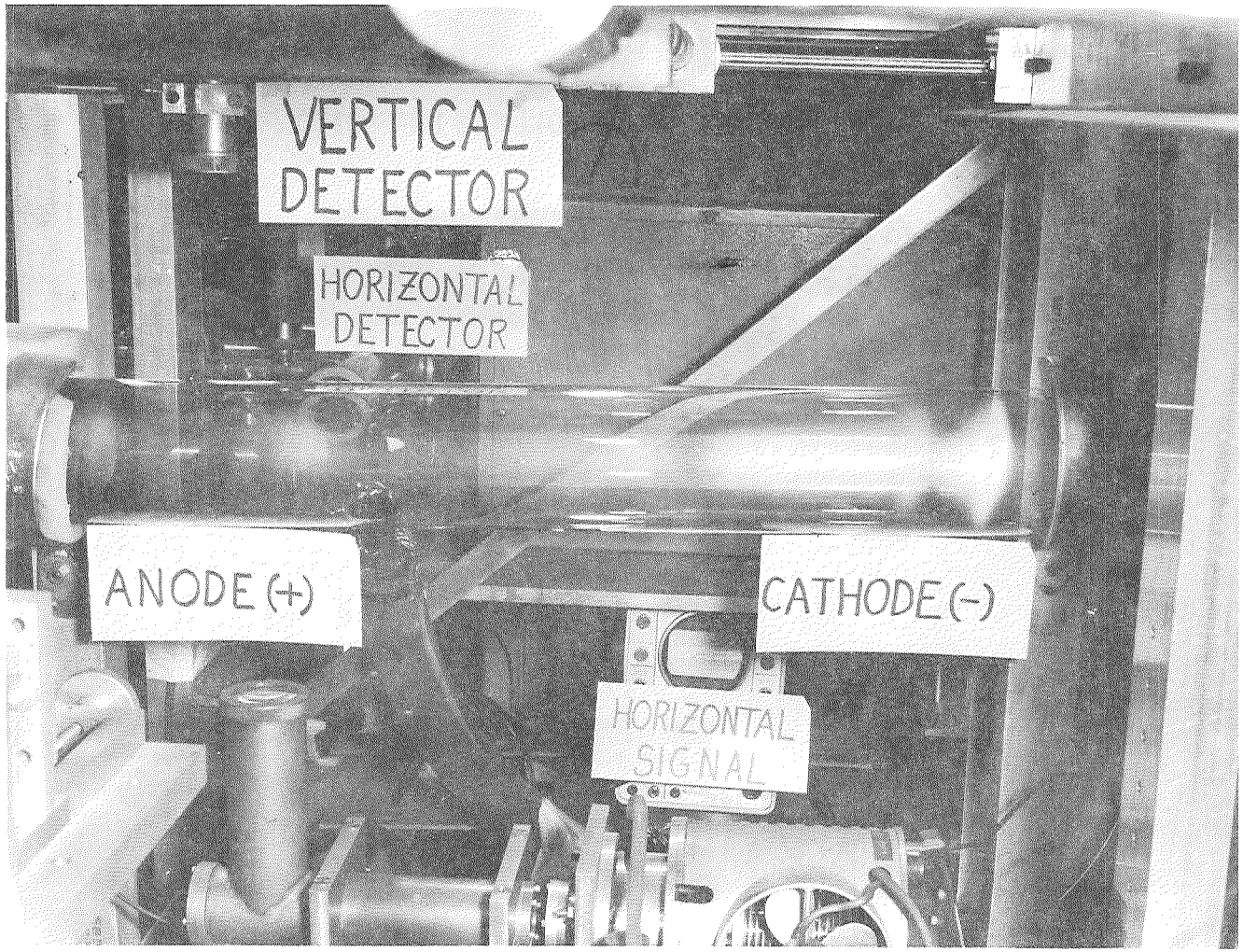


FIGURE II.2. EQUIPMENT SETUP

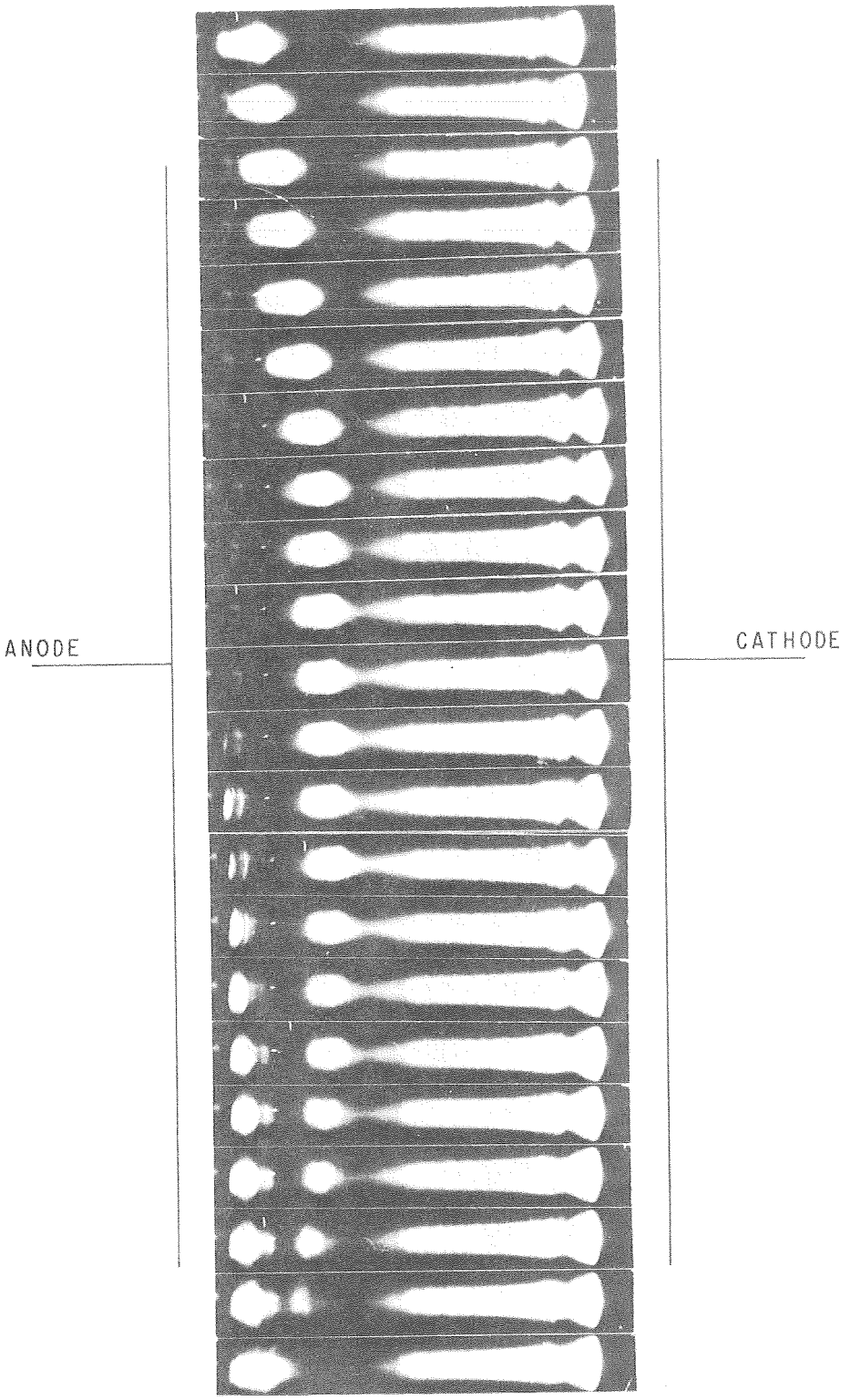


FIGURE II.3. ION STRIATION

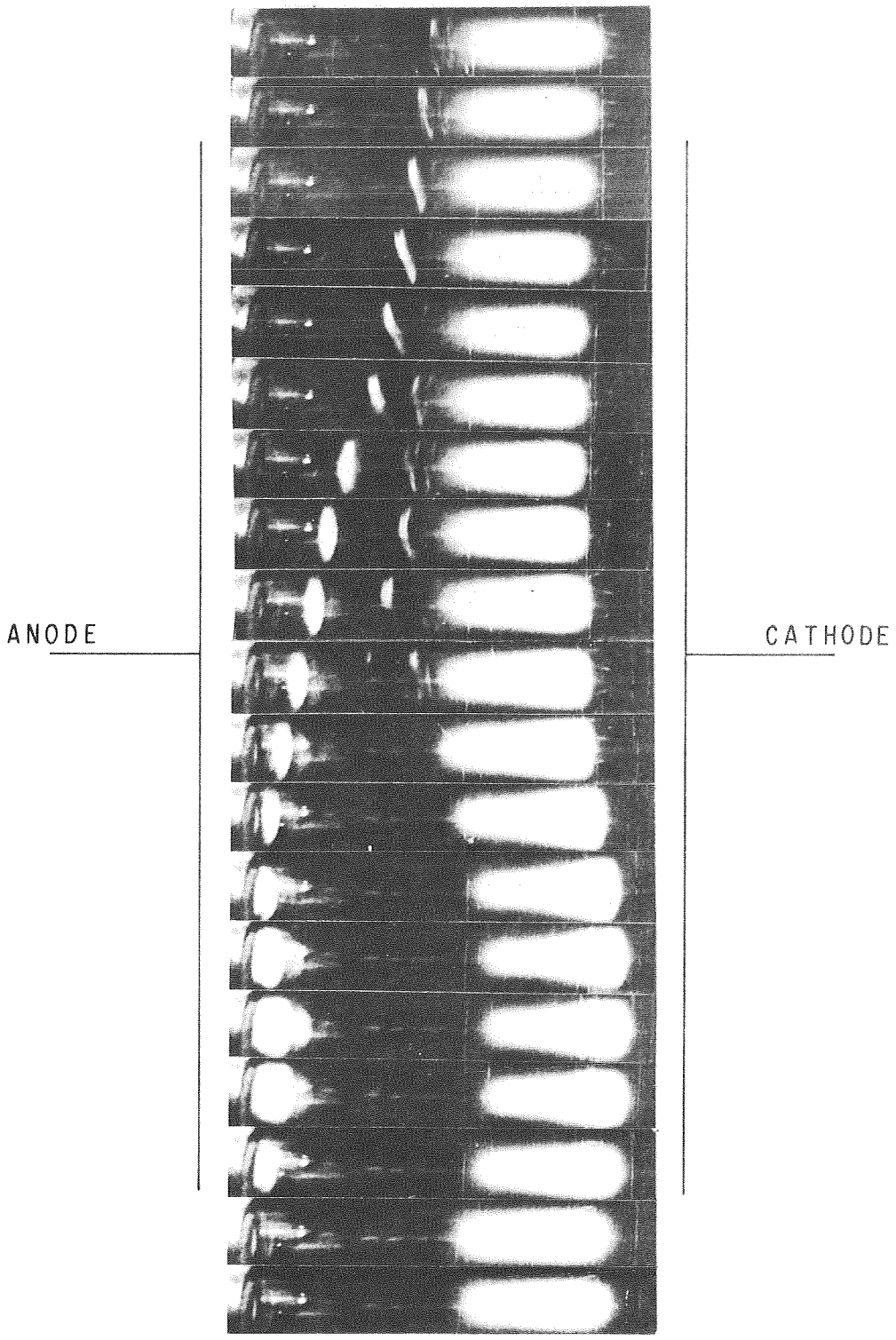


FIGURE II.4. ELECTRON STRIATION

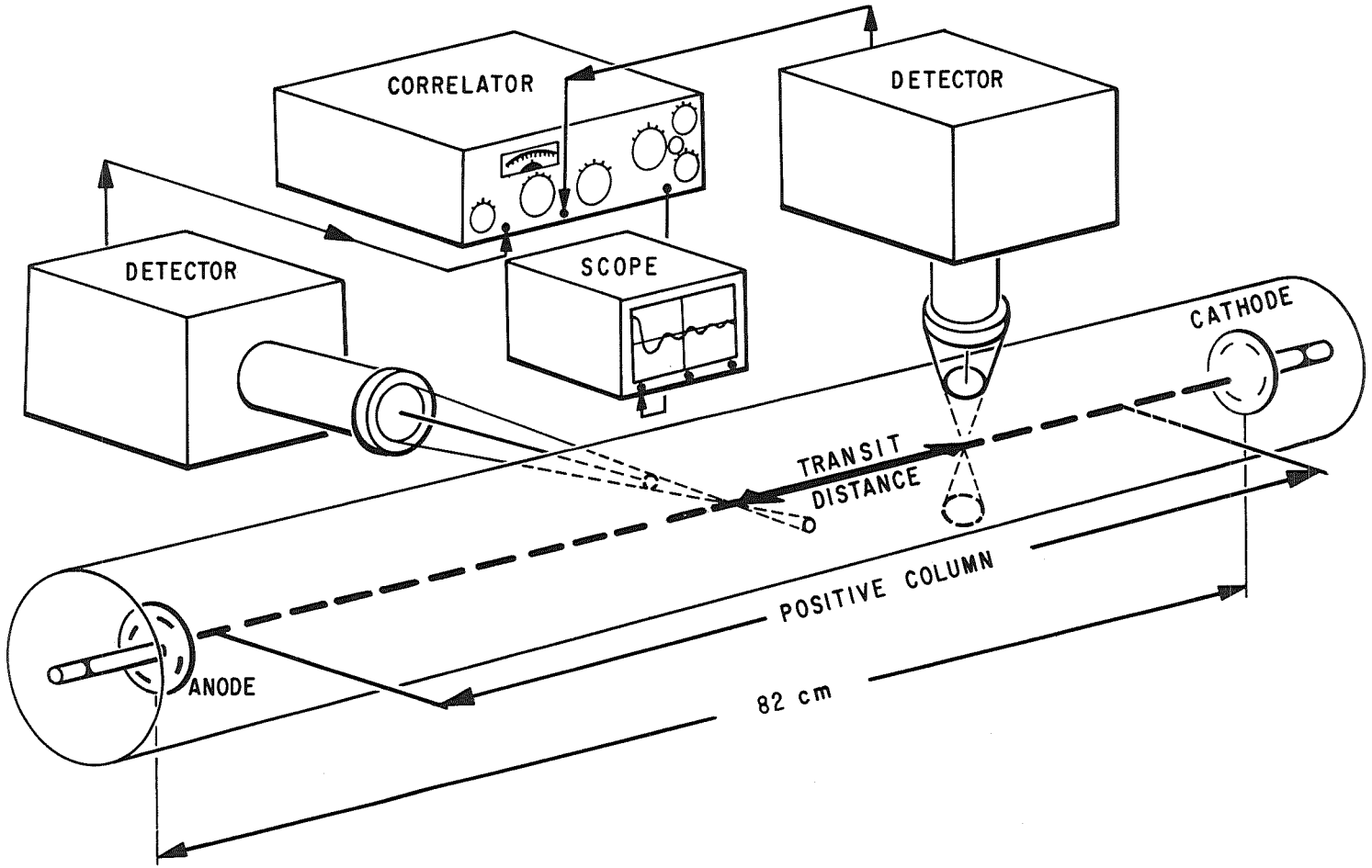


FIGURE II.5. EXPERIMENTAL SETUP FOR GLOW DISCHARGE

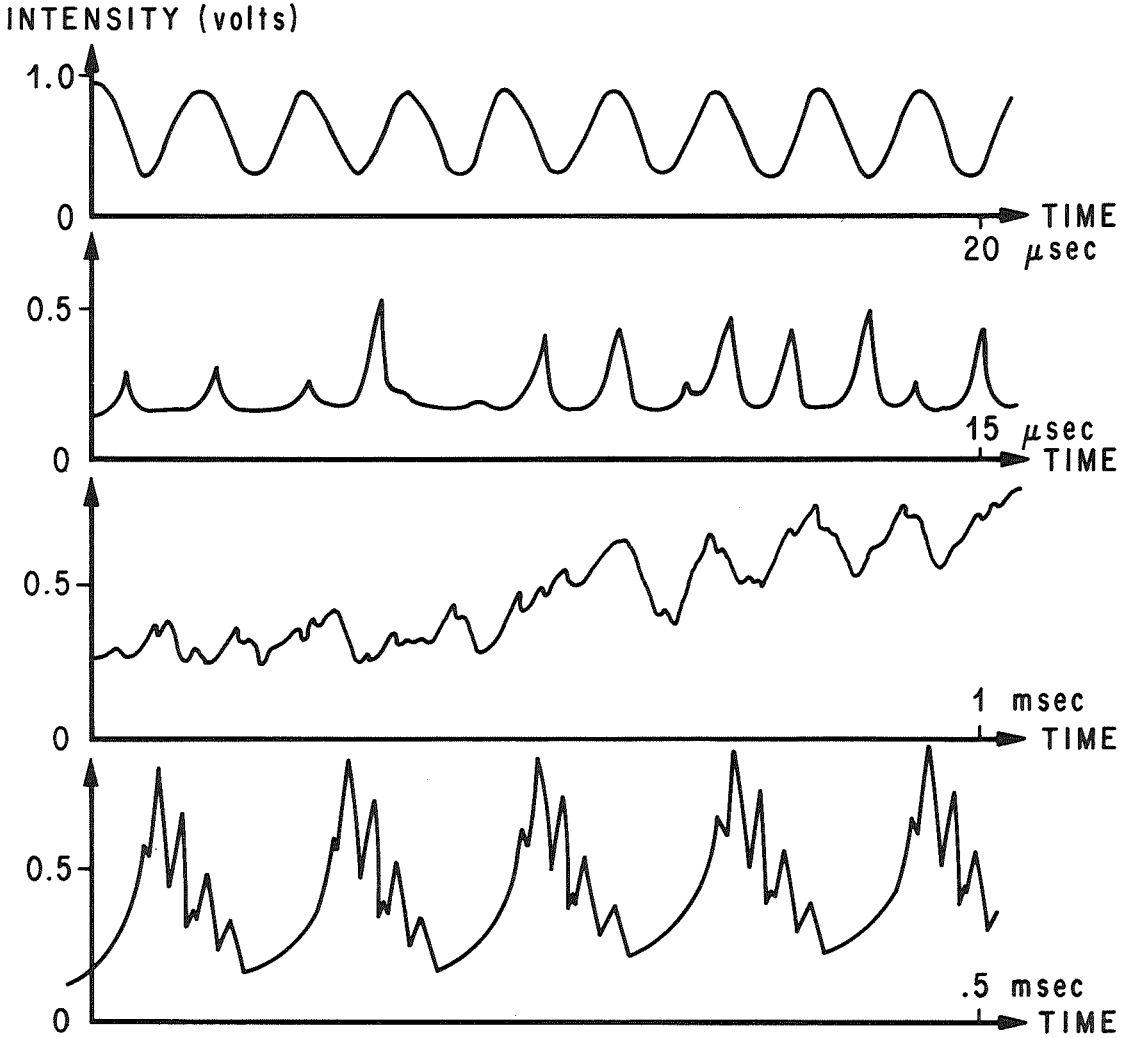


FIGURE II.6. MODES OF FLUCTUATION ENCOUNTERED IN GLOW DISCHARGE PRESSURE RANGE FROM 1 TO 25 MM HG AT 3100 Å AND BANDWIDTH OF 50 Å

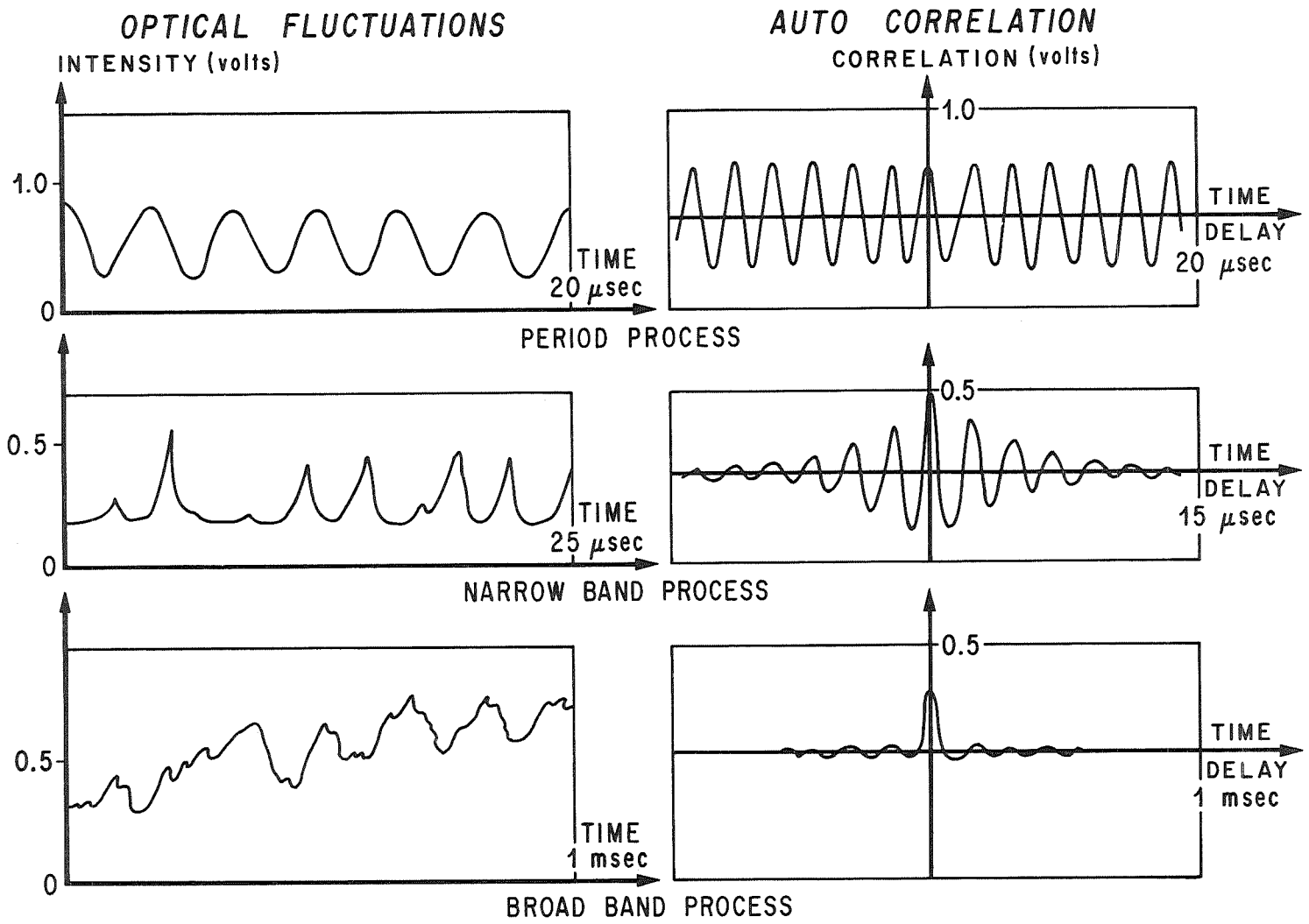


FIGURE II.7. CORRELATION OF SINGLE PHOTOMETER OUTPUTS FOR TYPICAL FLUCTUATIONS

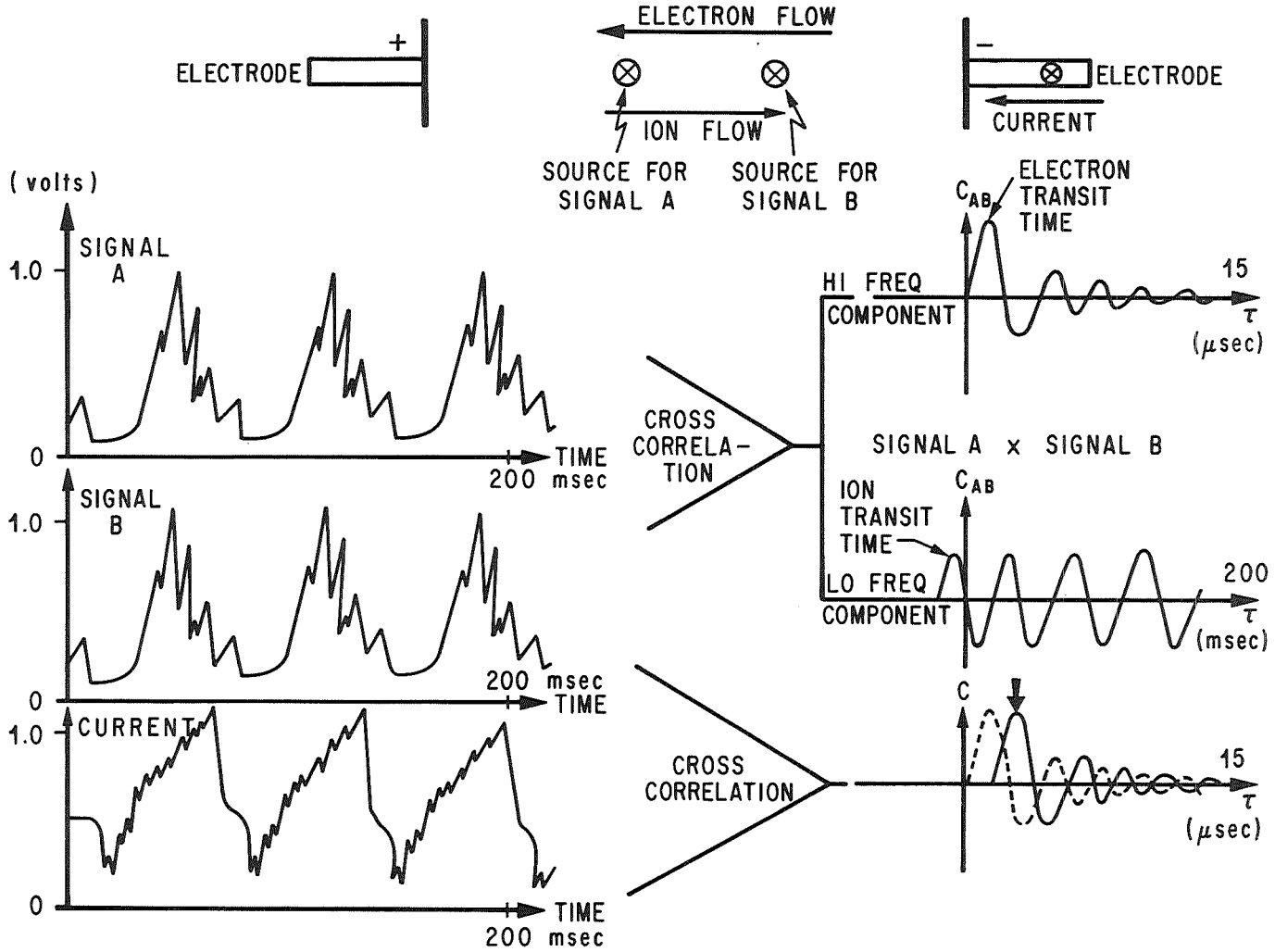


FIGURE II.8. SEPARATION OF ELECTRON AND ION STRIATIONS

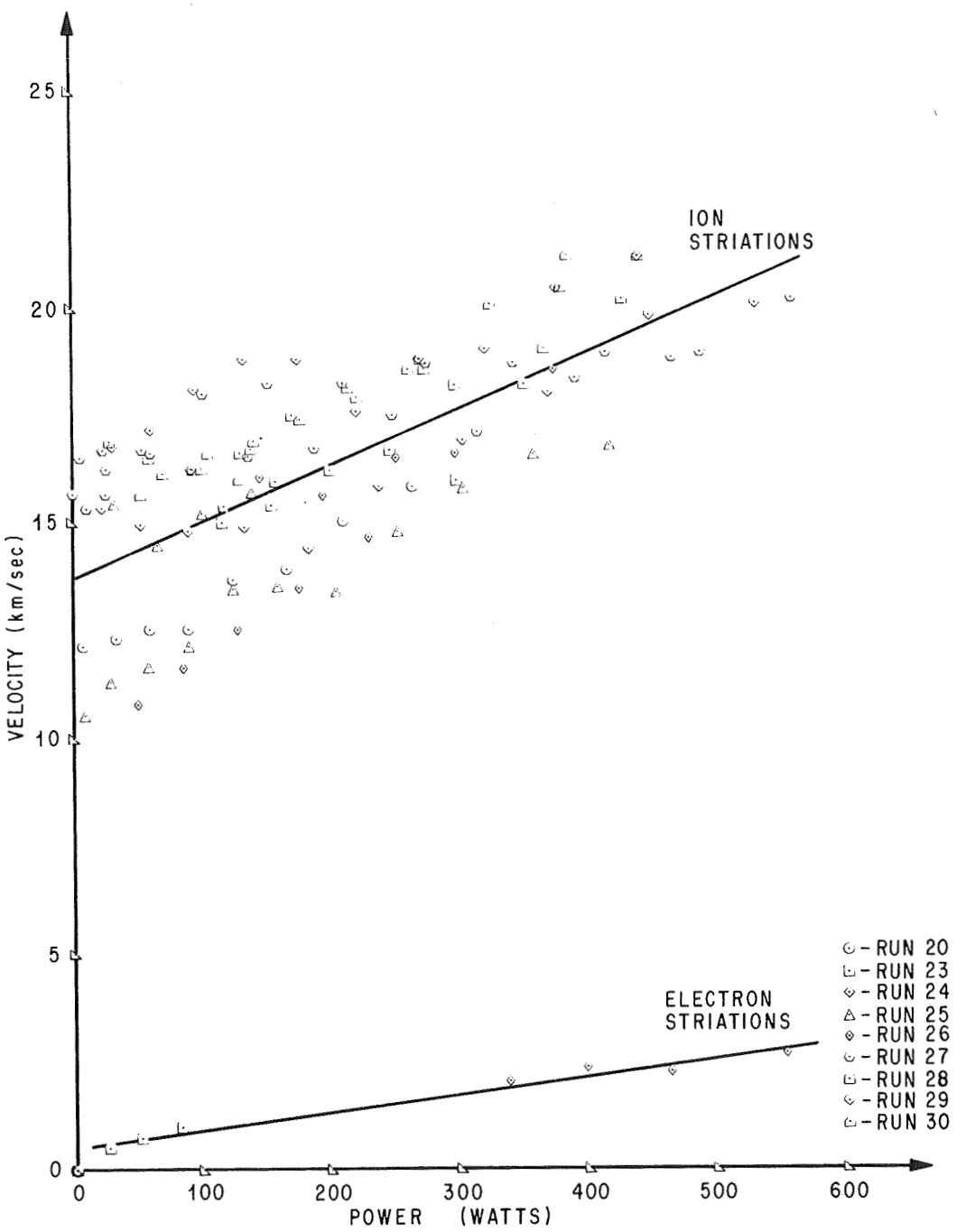


FIGURE II.9. EFFECT OF STRIATION DIRECTION ON ITS VELOCITY

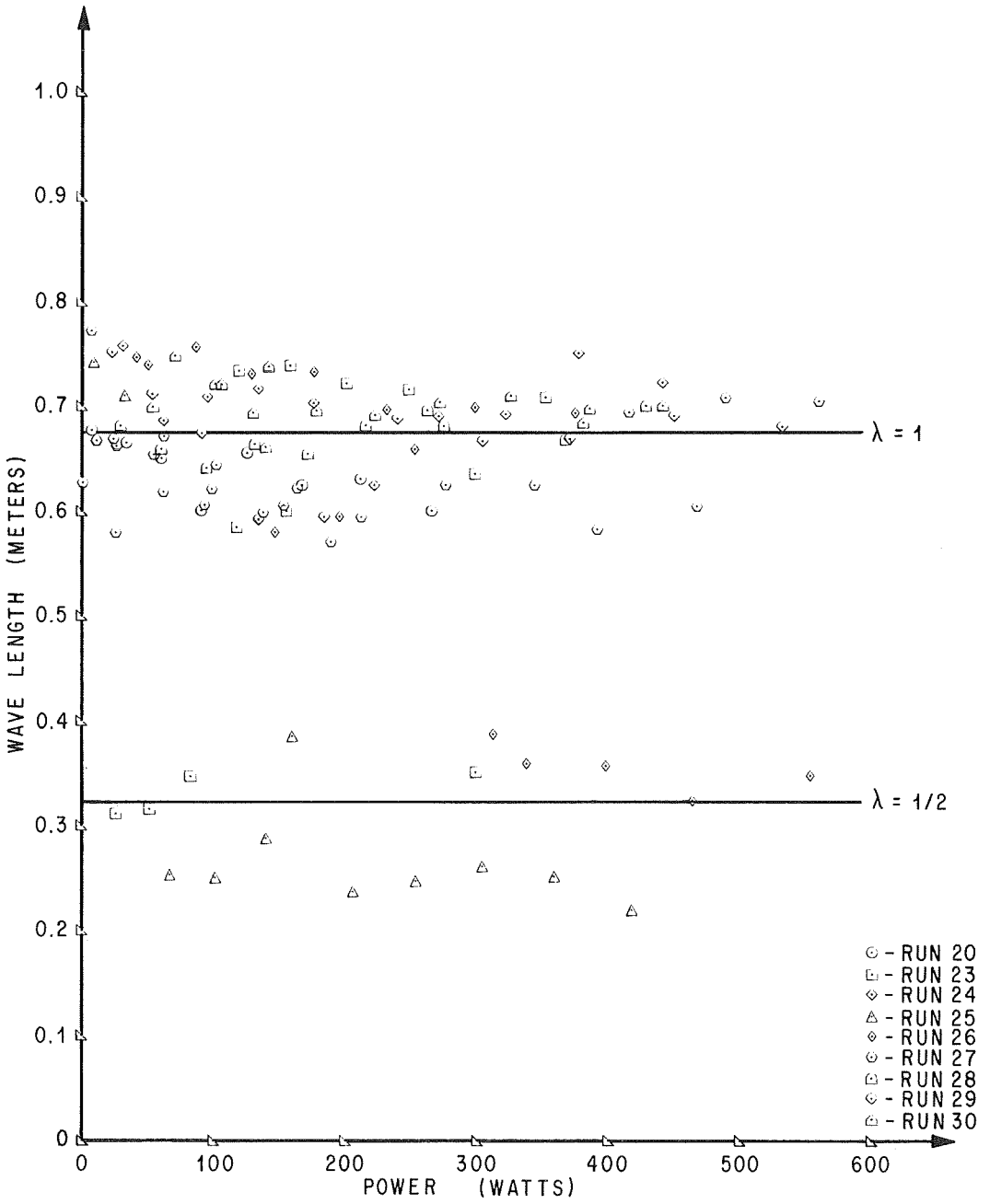


FIGURE II.10. QUANTUM EFFECT OF WAVELENGTH

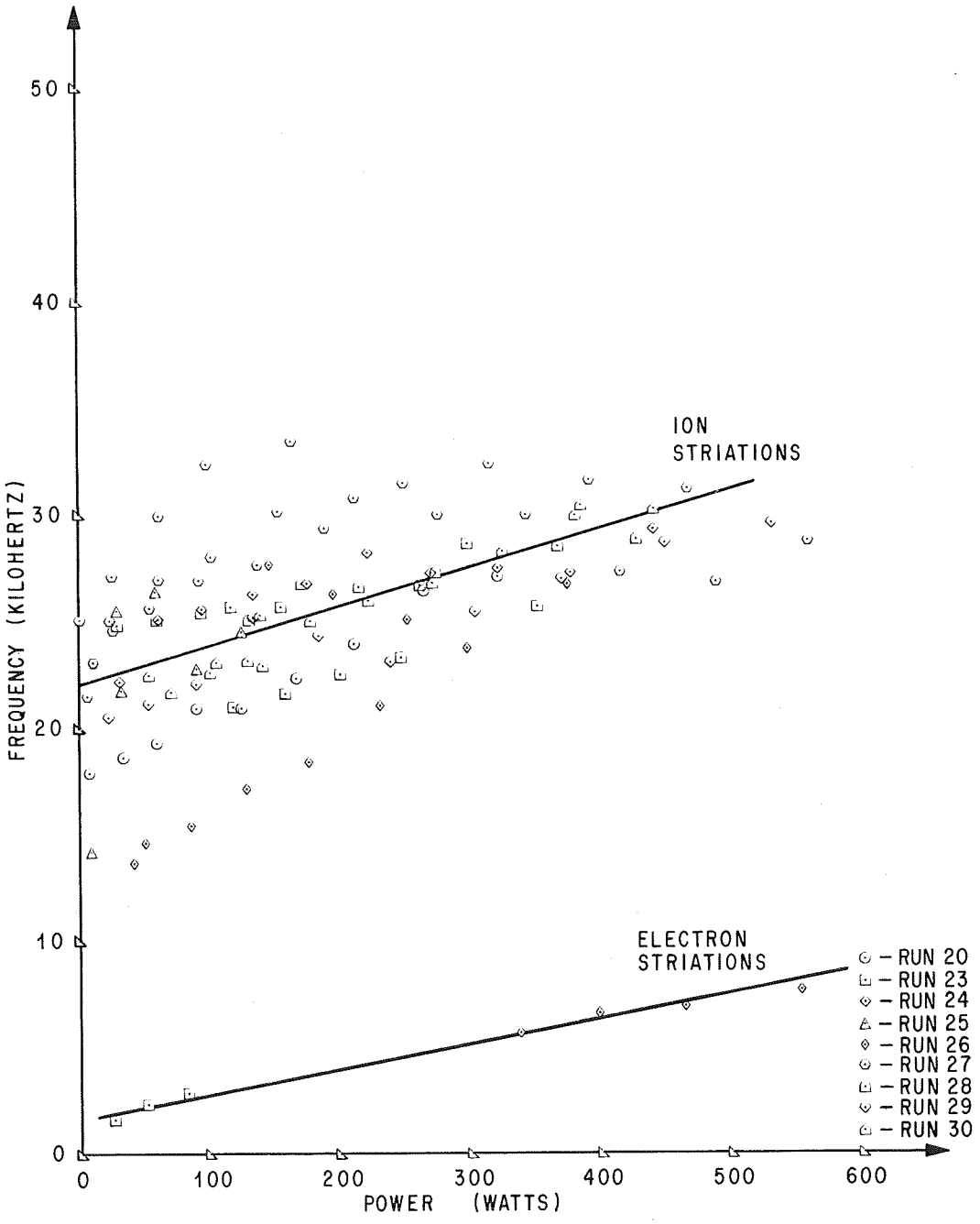


FIGURE II.11. EFFECT OF STRIATION DIRECTION ON ITS FREQUENCY

TABLE II.1. EXPERIMENTAL DATA

GLOW DISCHARGE IN ARGON

RUN NUMBER = 20.0 PRESSURE = 5.0

POWER WATTS	RESIST K OHMS	FREQ KHZ	VEL KM/SEC	WLG METERS	DIS I MA	DIS V VOLTS	PER USEC	TAU USEC
8.100	36.000	17.857	12.097	.677	15.0	540.0	56.0	24.8
33.605	7.954	18.519	12.295	.664	65.0	517.0	54.0	24.4
59.800	4.522	19.231	12.500	.650	115.0	520.0	52.0	24.0
90.255	3.315	20.833	12.500	.600	165.0	547.0	48.0	24.0
125.560	2.716	20.833	13.636	.655	215.0	584.0	48.0	22.0
166.950	2.377	22.222	13.889	.625	265.0	630.0	45.0	21.6
211.050	2.127	23.810	15.000	.630	315.0	670.0	42.0	20.0
264.625	1.986	26.316	15.789	.600	365.0	725.0	38.0	19.0
321.625	1.867	27.027	21.429	.793	415.0	775.0	37.0	14.0

RUN NUMBER = 23.0 PRESSURE = 4.8

POWER WATTS	RESIST K OHMS	FREQ KHZ	VEL KM/SEC	WLG METERS	DIS I MA	DIS V VOLTS	PER USEC	TAU USEC
25.650	10.260	1.600	.498	.311	50.0	513.0	625.0	603.0
51.500	5.150	2.353	.744	.316	100.0	515.0	425.0	403.0
82.500	3.667	2.857	.990	.347	150.0	550.0	350.0	303.0
117.000	2.925	25.641	15.000	.585	200.0	585.0	39.0	20.0
155.000	2.480	25.641	15.385	.600	250.0	620.0	39.0	19.5
297.600	1.860	28.571	18.182	.636	400.0	744.0	35.0	16.5
351.450	1.736	25.641	18.182	.709	450.0	781.0	39.0	16.5
298.000	1.862	45.455	15.957	.351	400.0	745.0	22.0	18.8
247.450	2.020	23.256	16.667	.717	350.0	707.0	43.0	18.0
200.400	2.227	22.472	16.216	.722	300.0	668.0	44.5	18.5
158.000	2.528	21.598	15.957	.739	250.0	632.0	46.3	18.8
118.200	2.955	20.964	15.385	.734	200.0	591.0	47.7	19.5

RUN NUMBER = 24.0 PRESSURE = 4.9

POWER WATTS	RESIST K OHMS	FREQ KHZ	VEL KM/SEC	WLG METERS	DIS I MA	DIS V VOLTS	PER USEC	TAU USEC
30.900	12.360	22.124	16.760	.758	50.0	618.0	45.2	17.9
61.800	6.180	25.000	17.143	.686	100.0	618.0	40.0	17.5
95.550	4.247	25.510	18.072	.708	150.0	637.0	39.2	16.6
134.000	3.350	26.178	18.750	.716	200.0	670.0	38.2	16.0
175.750	2.812	26.667	18.750	.703	250.0	703.0	37.5	16.0
221.700	2.463	28.090	17.544	.625	300.0	739.0	35.6	17.1
269.850	2.203	27.174	18.750	.690	350.0	771.0	36.8	16.0
321.200	2.007	27.397	18.987	.693	400.0	803.0	36.5	15.8
376.650	1.860	27.174	20.408	.751	450.0	837.0	36.8	14.7
440.000	1.760	29.240	21.127	.723	500.0	880.0	34.2	14.2

TABLE II.1. (Continued)

RUN NUMBER = 25.0 PRESSURE = 9.8

POWER WATTS	RESIST K OHMS	FREQ KHZ	VEL KM/SEC	WLG METERS	DIS I MA	DIS V VOLTS	PER USEC	TAU USEC
8.970	39.867	14.184	10.526	.742	15.0	598.0	70.5	28.5
29.500	11.800	25.510	11.321	.444	50.0	590.0	39.2	26.5
59.300	5.930	26.385	11.673	.442	100.0	593.0	37.9	25.7
90.750	4.033	22.779	12.146	.533	150.0	605.0	43.9	24.7
125.600	3.140	24.510	13.453	.549	200.0	628.0	40.8	22.3
160.000	2.560	35.088	13.514	.385	250.0	640.0	28.5	22.2
205.500	2.283	56.497	13.393	.237	300.0	685.0	17.7	22.4
253.050	2.066	59.524	14.778	.248	350.0	723.0	16.8	20.3
303.600	1.897	60.241	15.789	.262	400.0	759.0	16.6	19.0
358.200	1.769	65.789	16.575	.252	450.0	796.0	15.2	18.1
417.500	1.670	76.336	16.760	.220	500.0	835.0	13.1	17.9
139.200	3.480	54.348	15.707	.289	200.0	696.0	18.4	19.1
101.400	4.507	60.606	15.228	.251	150.0	676.0	16.5	19.7
66.500	6.650	57.143	14.493	.254	100.0	665.0	17.5	20.7
32.700	13.080	21.739	15.464	.711	50.0	654.0	46.0	19.4

RUN NUMBER = 28.0 PRESSURE = 5.1

POWER WATTS	RESIST K OHMS	FREQ KHZ	VEL KM/SEC	WLG METERS	DIS I MA	DIS V VOLTS	PER USEC	TAU USEC
30.400	12.160	24.752	16.854	.681	50.0	608.0	40.4	17.8
60.800	6.080	25.000	16.484	.659	100.0	608.0	40.0	18.2
94.800	4.213	25.316	16.216	.641	150.0	632.0	39.5	18.5
131.400	3.285	25.000	16.575	.663	200.0	657.0	40.0	18.1
171.750	2.748	26.667	17.442	.654	250.0	687.0	37.5	17.2
215.400	2.393	26.525	18.072	.681	300.0	718.0	37.7	16.6
262.150	2.140	26.596	18.519	.696	350.0	749.0	37.6	16.2
274.000	1.712	27.174	18.519	.681	400.0	685.0	36.8	16.2
367.650	1.816	28.409	18.987	.668	450.0	817.0	35.2	15.8
428.000	1.712	28.736	20.134	.701	500.0	856.0	34.8	14.9

RUN NUMBER = 29.0 PRESSURE = 2.0

POWER WATTS	RESIST K OHMS	FREQ KHZ	VEL KM/SEC	WLG METERS	DIS I MA	DIS V VOLTS	PER USEC	TAU USEC
23.250	9.300	20.408	15.306	.750	50.0	465.0	49.0	19.6
53.800	5.380	21.008	14.925	.710	100.0	538.0	47.6	20.1
91.050	4.047	21.930	14.778	.674	150.0	607.0	45.6	20.3
134.600	3.365	25.126	14.851	.591	200.0	673.0	39.8	20.2
184.250	2.948	24.213	14.354	.593	250.0	737.0	41.3	20.5
239.400	2.660	22.989	15.789	.687	300.0	798.0	43.5	19.0
303.800	2.480	25.316	16.854	.666	350.0	868.0	39.5	17.8
370.400	2.315	26.882	17.964	.668	400.0	926.0	37.2	16.7
449.550	2.220	28.571	19.737	.691	450.0	999.0	35.0	15.2
531.500	2.126	29.412	20.000	.680	500.0	1063.0	34.0	15.0

RUN NUMBER = 30.0 PRESSURE = 9.8

POWER WATTS	RESIST K OHMS	FREQ KHZ	VEL KM/SEC	WLG METERS	DIS I MA	DIS V VOLTS	PER USEC	TAU USEC
129.584	3.912	23.041	15.957	.693	182.0	712.0	43.4	18.8
141.400	3.535	22.831	16.854	.738	200.0	707.0	43.8	17.8
105.900	4.707	22.989	16.575	.721	150.0	706.0	43.5	18.1
70.900	7.090	21.598	16.129	.747	100.0	709.0	46.3	18.6
54.450	9.680	22.371	15.625	.698	75.0	726.0	44.7	19.2
101.700	4.520	22.523	16.216	.720	150.0	678.0	44.4	18.5
139.600	3.490	25.253	16.667	.660	200.0	698.0	39.6	18.0
178.000	2.848	24.938	17.341	.695	250.0	712.0	40.1	17.3
222.600	2.473	25.840	17.857	.691	300.0	742.0	38.7	16.8
271.250	2.214	26.667	18.750	.703	350.0	775.0	37.5	16.0
325.200	2.032	28.169	20.000	.710	400.0	813.0	35.5	15.0
380.250	1.878	29.851	20.408	.684	450.0	845.0	33.5	14.7
440.500	1.762	30.120	21.127	.701	500.0	881.0	33.2	14.2
385.650	1.904	30.303	21.127	.697	450.0	857.0	33.0	14.2

TABLE II.1. (CONTINUED)

RUN NUMBER = 26.0 PRESSURE = 2.0

POWER WATTS	RESIST K OHMS	FREQ KHZ	VEL KM/SEC	WLG METERS	DIS I MA	DIS V VOLTS	PER USEC	TAU USEC
41.905	5.800	13.605	10.169	.747	85.0	493.0	73.5	29.5
51.100	5.110	14.599	10.791	.739	100.0	511.0	68.5	27.8
86.250	3.833	15.385	11.628	.756	150.0	575.0	65.0	25.8
128.600	3.215	17.094	12.500	.731	200.0	643.0	58.5	24.0
176.250	2.820	18.349	13.453	.733	250.0	705.0	54.5	22.3
231.000	2.567	21.008	14.634	.697	300.0	770.0	47.6	20.5
297.500	2.429	23.697	16.575	.699	350.0	850.0	42.2	18.1
374.000	2.337	26.667	18.519	.694	400.0	935.0	37.5	16.2
463.500	2.289	6.849	2.222	.324	450.0	1030.0	146.0	135.0
553.000	2.212	7.634	2.655	.348	500.0	1106.0	131.0	113.0
397.200	2.482	6.557	2.344	.357	400.0	993.0	152.5	128.0
337.050	2.751	5.650	-2.027	-.359	350.0	963.0	177.0	-148.0
146.000	3.650	27.624	16.043	.581	200.0	730.0	36.2	18.7
195.500	3.128	26.247	15.625	.595	250.0	782.0	38.1	19.2
252.000	2.800	25.000	16.484	.659	300.0	840.0	40.0	18.2
311.500	2.543	15.674	21.739	1.387	350.0	890.0	63.8	13.8

RUN NUMBER = 27.0 PRESSURE = 1.9

POWER WATTS	RESIST K OHMS	FREQ KHZ	VEL KM/SEC	WLG METERS	DIS I MA	DIS V VOLTS	PER USEC	TAU USEC
163.590	3.710	33.333	20.690	.621	210.0	779.0	30.0	14.5
99.000	4.400	32.258	20.000	.620	150.0	660.0	31.0	15.0
62.100	6.210	29.851	20.000	.670	100.0	621.0	33.5	15.0
26.200	10.480	27.027	15.625	.578	50.0	524.0	37.0	19.2
1.207	1.932	25.000	15.625	.625	25.0	48.3	40.0	19.2
25.000	10.000	24.938	16.667	.668	50.0	500.0	40.1	18.0
55.300	5.530	25.510	16.667	.653	100.0	553.0	39.2	18.0
93.150	4.140	26.810	16.216	.605	150.0	621.0	37.3	18.5
137.600	3.440	27.548	16.484	.598	200.0	688.0	36.3	18.2
189.000	3.024	29.240	16.667	.570	250.0	756.0	34.2	18.0
249.600	2.773	31.348	17.442	.556	300.0	832.0	31.9	17.2
315.350	2.574	32.258	17.045	.528	350.0	901.0	31.0	17.6
391.200	2.445	31.447	18.293	.582	400.0	978.0	31.8	16.4
467.100	2.307	31.056	18.750	.604	450.0	1038.0	32.2	16.0
559.000	2.236	28.571	20.134	.705	500.0	1118.0	35.0	14.9
488.700	2.413	26.667	18.868	.708	450.0	1086.0	37.5	15.9
415.200	2.595	27.174	18.868	.694	400.0	1038.0	36.8	15.9
343.000	2.800	29.851	18.634	.624	350.0	980.0	33.5	16.1
275.700	3.063	29.851	18.634	.624	300.0	919.0	33.5	16.1
211.750	3.388	30.675	18.182	.593	250.0	847.0	32.6	16.5
153.000	3.825	30.030	18.182	.605	200.0	765.0	33.3	16.5
102.300	4.547	27.933	17.964	.643	150.0	682.0	35.8	16.7
61.500	6.150	26.882	16.575	.617	100.0	615.0	37.2	18.1
26.650	10.660	24.510	16.216	.662	50.0	533.0	40.8	18.5
12.025	19.240	22.989	15.306	.666	25.0	481.0	43.5	19.6
12.025	19.240	22.989	15.306	.666	25.0	481.0	43.5	19.6
7.095	31.533	21.368	16.484	.771	15.0	473.0	46.8	18.2

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